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13. ABSTRACT (Maximum 200 words)

We developed robotic algorithms for chemical plume tracking based on the well-known behavior of lobsters to track odor plumes to their source such as traps. In a 7-meter flume we tested lobster behavior in food odor plumes under different source conditions of flow, turbulence and intermittency. We found that lobsters can track many different plumes but that plume gaps interfere with performance. In the same flume, robots using only fluorecence detectors (as proxies for chemical detection) tracked dye plumes under simple conditions of coherent plumes; their performance deteriorated quickly with distance (detection threshold) and plume meander creating gaps. We suggested that robots with additional flow sensors would more closely resemble lobsters and match their performance. Performance improved significantly when we added a gyroscope-based direction sensor as a proxy for mean flow detection. Finally, algorithms using immediately recent memory outperformed those that did not. We expect further robotic performance improvements with the addition of fine scale flow detectors similar to the lobsters' hydrodynamic sensors. Such sensors of the proper scale and bandwidth were not available for this project. Outside the laboratory flume the robot was tested successfully in 5-meter water depth in Eilat, Israel, showing its real world capabilities.

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Final Report

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PRINCIPAL INVESTIGATOR: Dr. Jelle Atema

INSTITUTION: Boston University Marine Program

GRANT TITLE: "Odor Plume Tracing: Lobster Inspired Algorithms"

AWARD PERIOD: 1 September 1998 - 30 September 2001

OBJECTIVE: To discover and understand strategies for tracking chemical plumes to their source in environments characterized by turbulent flow.

APPROACH: Two parallel approaches were used. We studied the behavior of plume-tracking lobsters in the laboratory. We also studied plume tracking by autonomous underwater robots under identical conditions to those under which the lobsters were studied. Lobster performance was used as a benchmark to set performance goals for the robots. Hypothesis testing with the robots was used to exclude unworkable strategies as explanations for lobster behavior.

ACCOMPLISHMENTS:

Designed, built and validated two autonomous, underwater lobster robots capable of tracking chemical plumes under benthic lab conditions.

Designed and built novel chemical sensors capable of sensing plumes at the temporal, spatial and concentration scales of the American lobster.

Made parametric studies nine variants of the effectiveness of the odor gated rheotaxis strategy under the same fluid mechanical regime in which the lobster was tested.

Extended the study of the best performing of the nine algorithms (above) in other ONR funded laboratories. Specifically to conditions used to test the blue crab (Georgia Tech) and with quantified low frequency meander (Cornell).

Investigated the effects of variation in the fine-scale structure of odour plumes that result from differences in 1) distance from the odour source (4m versus 7m starting position for animal) and 2) characteristics of the odor source itself (a "leaky" source versus a "jet" source) on the tracking behaviour of lobsters. No differences were found in the percentage of lobsters that tracked "leaky" versus "jet" sources; however, the paths they took indicate that odor-patch intermittency may provide information to the orienting animal (headings were more accurate in the "jet" condition versus the "leaky" condition). Animals did not appear to be using odor gated rheotaxis, based on the distribution of headings as a function of distance from the source. Animals navigating from 4m and 7m away from the source did not exhibit any significant differences in overall speed, headings, or accuracy in locating the odor source.

CONCLUSIONS:
Odor gated rheotaxis leads to more efficient tracking in turbulent conditions than pure chemical sensing. Algorithms that employ memory of recent experience in the plume perform significantly better than those that do not. The best parametrically tuned algorithms that employ mean flow sense (rheotaxis) and memory cannot perform as well as the American lobster and probably the blue crab.

SIGNIFICANCE: We made significant progress in understanding the plume tracking problem but animal performance provides an existence proof that there is still significant performance improvement to be obtained. Odor gated rheotaxis augmented with memory is an effective plume tracking strategy that can be implemented in existing underwater vehicles. It will work in well-defined (laboratory) plumes with low intermittancy but even under these conditions far more (time) efficient algorithms remain to be discovered.

AWARD INFORMATION:

PUBLICATIONS AND ABSTRACTS:

Refereed Publications In Professional Journals:

Basil, J., & Sandeman, D. (2000a). Crayfish (Cherax destructror) use Tactile Cues to Detect and Learn Topographical Changes in Their Environment. Ethology, 106, 247-259.
Basil, J. A., Hanlon, R. T., Sheikh, S. I., & Atema, J. (2000). Three-> Dimensional Odor Tracking By Nautilus Pompilius. Journal of Experimental Biology, 203(9), 1409-1414.
Basil, J. A., & Sandeman, D. (2000b). Crayfish (Cherax destructor) use Tactile Cues to Detect and Learn Spatial Changes in Their Environment. Ethology, In Press.
Blazis, D. E., & Grasso, F. W. (2001). Introduction to: Invertebrate Sensory Information Processing: Implications for Biologically-Inspired Autonomous Systems. Biological Bulletin, 200, 147-149.
Grasso, F., W., Consi, T., R., Mountain, D., C, & Atema, J. (1999a). Biomimetic robot lobster performs chemo-orientation in turbulence using a pair of spatially separated sensors:progress and challenges. Robotics and Autonomous Systems, 807, 1-17.
Grasso, F. W. (2001). Invertebrate-inspired sensory-motor systems and autonomous, olfactory-guided exploration. Biological Bulletin, 200(2), 160-168.
Hanna, J. P., Grasso, F. W., & Atema, J. (1999). Temporal correlation between sensor pairs in different plume positions: a study of concentration information available to the american lobster, Homarus americanus, during chemotaxis. Biological Bulletin, 197, 26-27.
Mjos, K., Grasso, F., & Atema, J. (1999). Antennule use by the American lobster, Homarus americanus, during chemo-orientation in three turbulent

odor plumes. Biological Bulletin, 197, 249-250.
Pohlman, K., Grasso, F. W., & Breithaupt, T. (2001). Tracking wakes: the nocturnal predatory strategy of piscivorous catfish. Proceedings of the National Academy of Science, 98, 7371-7374.

In Meeting Proceedings:

Grasso, F. W., Basil, J. A., & Atema, J. (1998a, September 14-17). Toward the convergence: robot and lobster perspectives of tracking odors to their source in the turbulent marine environment. Paper presented at the Proceedings of the 1998 IEEE, Gaithersburg, MD.
Mountain, D. C., Grasso, F. W., Consi, T. R., & Atema, J. (1998). Simulating Olfactory Scene Analysis with a Biomimetic Robot. Paper presented at the Proceedings of the 1999 IEEE 25th Annual Northeast Bioengineering Conference.

BOOK CHAPTERS:

Grasso, F. W. (2001a). Environmental Information, ANimal Behavior and BioRobot Design: Reflections on Locating Chemical Sources in Marine Enviornments. In B. Web & T. R. Consi (Eds.), Biorobotics: methods and applications (pp. 21-37). Cambridge, MA: AAAI Press/ MIT Press.
Grasso, F. W. (2001b). How robotic lobsters locate odor sources in turbulent water. In O. Holland & D. MacFarland (Eds.), Artificial Ethology (pp. 47-59). Oxford: Oxford University Press.
Grasso, F. W. (2002). Flow and chemo-sense for robot and lobster guidance in tracking chemical sources in turbulence. In J. Ayers, J. L. Davis, & A. Rudolph (Eds.), Neurotechnology for biomimetic robots (pp. 553-573). Cambridge: MIT Press.

ABSTRACTS:

Basil, J., R. Hanlon, S. Sheikh, and J. Atema (1998). Odor plume tracking by the living fossil, Nautilus pompilius. Chemical Senses 23.
Grasso, F., P. Beglane, J. Basil, and J. Atema (1998). Far Field Chemo-orientation in the American Lobster (Homarus americanus): A role for micro-mechanosensation? Chemical Senses 23.
Grasso, F. W., Borden, L. R., & Atema, J. (2000b). Flow- and chemo-sense for robot and lobster guidance in odor source tracking. Soc. Neurosci. Abst., 30, 368.3.
Grasso, F. W., Borden, L. R., & Atema, J. (2000c). Of lobsters, robots, and plumes: odor tracking in a turbulent world. Animal Behavior Society Abstracts, #79, 37.
Grasso, F. W., Gaito, S. T., & Atema, J. (1999c). Behavior, Peripheral Chemo-Reception and Information in Turbulent Odor Plume Tracking: Results from Simulation Studies. Soc. Neurosci. Abst., 29(1), #550.3.

Grasso, F. W., Voigt, R., & Atema, J. (1998b). Lobster Chemoreceptor Dynamics in Turbulent Odor Plumes: Transmission of Environmental Cues from the Periphery to the CNS. Society for Neuroscience Abstracts, 28, #711.2.>
Grasso, F. W., Voigt, R., & Atema, J. (2000a).> Dynamic Filter Properties of Lobster-Nose Chemo-Receptors: Peak Performance Evaluation. Computational Neuroscience, CNS* 2000.
Kam, A., Grasso, F. W., & Atema, J. (1998). Use of antennule flicking in odor source tracking of the lobster, Homarus americanus. Paper presented at the MBL General Scientific Meetings, Woods Hole, MA.
Voigt, R., Basil, J., and J. Atema (2001) American lobsters track and locate distant "leaky" odor sources. Chemical Senses 24.